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 FOR OCTOBER, NOVEMBER AND DECEMBER, 1964

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Aerodynamic Noise Research Support
 for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
 GEORGE C. MARSHALL SPACE FLIGHT CENTER
 HUNTSVILLE, ALABAMA

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The work under the present contract has been defined as Aerodynamic Noise Research Support with particular reference to the problem of the prediction of aerodynamic pressure fluctuations on large space vehicles. Wyle's work under this contract started with a review of the known work on aerodynamic pressure fluctuations, and it was apparent that the major sources of these fluctuations, viz: separated flow and oscillating shocks, were very far from being understood. The first requirement was to predict the position and extent of these flows and it is felt that this prediction problem has been substantially solved by the concept of the separation region being a constant angle wedge in the flow. This concept together with a review and analysis of the available information was presented in the first Quarterly Progress Report.

At that time future work under the contract was defined under four main headings

- (i) assistance to M.S.F.C. in interpretation of the results from the tests at Ames
- (ii) a theoretical investigation of separated flow fields using mean flow parameters
- (iii) a theoretical study of the generation of pressure turbulence fluctuations with particular reference to separated flows
- (iv) an experimental investigation into subsonic turbulent separated flows in the low speed wind tunnel of the Wyle Aerodynamics Facility.

It is expected that work will commence under heading (i) during the next quarter as soon

as further data from Ames becomes available.

During the last quarter several attempts were made to produce a theory under heading (ii). However these have not produced successful results because of the non-existence of experimental information on a turbulent separated flow region, particularly the lack of information on the mean velocity profiles. It is hoped that this information will be obtained from the experimental program.

Under heading (iii) some success has been achieved. The work is reported in detail in Appendix A of this report. It was not clear how far the current theories for the wall pressure fluctuations in the attached case could be applied to the case of a separated boundary layer. Therefore the equations governing the pressure fluctuation were studied and it has been shown how a number of new generation terms will be present on a separated flow. Predictions can be made from this theory, but an important discrepancy between these predictions and the one reported experimental result has been found. The resolution of this discrepancy is thought to represent the key to a full understanding of supersonic separated flows, and may well lead to an improved understanding of attached flows. In addition a new hypothesis has been advanced which gives a better basis for a physical understanding of the mechanisms at work in the attached boundary layer. The hypothesis is shown to explain all the known facts of the pressure fluctuation phenomena.

The experimental program (heading iv above) is planned to commence this year and the special separated flow test section is designed and awaits fabrication. Due to delays at Wyle the program is not expected to start until February rather than in January as was first intended. The experimental program is described in detail in Appendix B of this report.

As part of the general program of Aerodynamic Noise Research Support some additional work has taken place on the fundamental processes of aerodynamic noise generation. This work was commenced by a member of the staff before the current contract period and the present work consisted of refinement and improved interpretation. A report on the work is included herewith as Enclosure A. In summary, the work deals with the basic effects of acceleration on sound generation. The effects on simple sources, point forces, and point acoustic stresses are considered and a number of interesting and practically significant effects emerge. This work has many applications both within and outside the field of space vehicles. Examples include cavity resonances, noise from panel vibration, vortex noise from rotating systems, helicopter noise, noise from tip jet rotors, deflected rocket noise, and even, as suggested in Appendix A, the noise and pressure fluctuations resulting from boundary layers and exhaust flows. The work has not been previously published.

During December two meetings were held with MSFC staff, and as a result it was agreed that Wyle should produce a report giving a prediction technique for the aerodynamic pressure fluctuations on space vehicles. This report will contain a full discussion of the various phenomena occurring and a separate method for their prediction. At the present time it seems that the position and extent of the leading sources of pressure fluctuation can be defined following the ideas put forward in the last Quarterly Progress Report. The magnitude of the fluctuations can also be predicted with reasonable accuracy. The position for frequency

spectrum is much less satisfactory, and only very limited flight data are available. Knowledge of correlation patterns is even less, and for these there is no flight data. The report will necessarily reflect the inadequacies in the experimental data, but will be designed so that it may be readily updated as better information becomes available. The report will be produced, in its preliminary form, before the end of February.

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APPENDIX A
PRESSURE FLUCTUATIONS IN TURBULENT BOUNDARY LAYERS
SUMMARY

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In this report the equations governing the pressure fluctuations in a turbulent boundary layer are derived following the known methods for incompressible flow. The case of the attached turbulent boundary layer is discussed and the hypothesis advanced that the major cause of wall pressure fluctuations is the intermittent eruption of the laminar sublayer which has been observed during flow visualization experiments. This hypothesis agrees with all the known features of boundary layer pressure fluctuations and offers a good physical framework for the understanding of their actions. The case of the separated turbulent boundary layer is then discussed. Application of the equations already derived shows how additional sources of pressure fluctuation may be present in the separated boundary layer compared to the attached case. Firstly the 'turbulence-turbulence' interaction terms may be important, and secondly it is shown how additional pressure fluctuations can arise from the interaction of the turbulence with the gradients of velocity in the free stream direction. The exact magnitude of these terms will not be known until more detailed experimental information becomes available. Finally it is shown how the conventional turbulence-mean shear interaction gives rise to pressure patterns which are convected at only a fraction of the free stream velocity. This contradicts the presently available supersonic experimental results and it is suggested that the new mechanisms of pressure fluctuation may be occurring in the supersonic separated flow case.

AUTHOR

1.0 INTRODUCTION

The first work on the estimation of the pressure fluctuations within turbulence was due to Heisenberg (Reference 1) and Batchelor (Reference 2). Their work referred to the highly idealized model of homogeneous (the same from point to point), isotropic (having no preferred orientation) turbulence. Even then considerable manipulation and approximation was required to derive a result. It was found that the root mean square value of the pressure fluctuations in homogeneous isotropic turbulence was given by

$$p_{rms} = 0.58 \rho \overline{u^2} \quad (1)$$

where ρ is the density and u is the velocity fluctuation. The magnitude of the velocity fluctuation will be the same for any direction in isotropic turbulence. In Reference (3) Uberoi made similar calculations using more detailed experimental results. These calculations gave an average value of about

$$p_{rms} = 0.7 \rho \overline{u^2} \quad (2)$$

All these calculations have relied on estimating the correlation patterns of the turbulent velocity fluctuations, and relating these to the pressure fluctuations via the Navier-Stokes equations and have all referred to incompressible flows. It is possible, in principle, to extend these calculations to include the effects of compressibility but this would be a highly complicated task, particularly because of the need to consider retarded time differences within the flow.

The results of equations (1) and (2) refer to the pressure fluctuations produced by turbulent interactions alone. This source of pressure fluctuations is the 'Turbulence-Turbulence' contribution. However, the majority of real flows will contain some mean shear, which has a pronounced effect on the pressure fluctuations which occur. This second contribution from the 'Turbulence-Mean Shear' interaction was first

investigated by Kraichnan in Reference 4, and in Reference 5 he extended this work to cover the case of wall pressure fluctuations in the turbulent boundary layer. Kraichnan's work has been reviewed and extended by Lilley, and Lilley and Hodgson (References 6 and 7).

Kraichnan's original calculations in Reference 5 indicated that the ratio of the turbulence-turbulence contribution to that of the turbulence-mean shear was 1:32. Hodgson has also made calculations (Reference 8) which give a ratio of 1:20. It would thus appear that it is the turbulence-mean shear interaction which gives the major contribution to the wall pressure fluctuations, and this result has been generally accepted. However, it should be pointed out that Corcos (Reference 9) has reported calculations which find the ratio to be only 1:1.6 so that the question cannot yet be considered as completely resolved.

In the following sections the equations for the boundary layer pressure fluctuations will first be derived and the various approximations required discussed. The contribution of both the turbulence-turbulence and of the turbulence-mean-shear interactions will be shown. The case of the attached turbulent boundary layer is discussed in detail and a new hypothesis is advanced offering a physical basis for the understanding of the pressure fluctuations. The equations are then applied to the separated boundary layer and it is shown how some of the approximations made for the attached case are no longer valid.

2.0 EQUATIONS FOR THE PRESSURE FLUCTUATIONS

2.1 Derivation of the Differential Equation

In this section the basic equations describing the pressure fluctuations are derived. The derivation here presented is an amalgam of the methods given in References 4 - 9. The analysis begins from the exact equations of aerodynamics which incorporate the effects of both viscosity and compressibility, and uses tensor notation with the summation convention.

The equation for the conservation of mass may be written as:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho v_i) = 0 \quad (3)$$

and the equation for the conservation of momentum is

$$\frac{\partial}{\partial t} (\rho v_i) + \frac{\partial}{\partial x_i} (\rho v_i v_i) + \frac{\partial}{\partial x_i} (p_{ij}) = 0 \quad (4)$$

Now experiment and theory agree that fluids show a linear dependence of viscous shear on velocity gradient so that the aerodynamic stress tensor p_{ij} is

$$p_{ij} = (p + \frac{2}{3} \mu e_{kk}) \delta_{ij} - 2 \mu e_{ij} \quad (5)$$

where p is the local static pressure and

$$e_{ij} = \frac{1}{2} \left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right) \quad \text{is the 'strain' tensor}$$

also

$$e_{kk} = \frac{\partial v_k}{\partial x_k}$$

The derivation of equation (5) is given in detail in Reference 10.

Differentiating equation (5) and rearranging gives

$$\frac{\partial p_{ii}}{\partial x_i} = \frac{\partial p}{\partial x_i} - \mu \left\{ \frac{1}{3} \frac{\partial}{\partial x_i} \left(\frac{\partial v_i}{\partial x_i} \right) + \frac{\partial^2 v_i}{\partial x_i^2} \right\} \quad (6)$$

Differentiating equation (4) with respect to x_i (equivalent to taking the divergence) and using equation (6) gives

$$0 = \frac{\partial}{\partial t} \frac{\partial (\rho v_i)}{\partial x_i} + \frac{\partial^2}{\partial x_i \partial x_i} (\rho v_i v_i) + \frac{\partial^2 p}{\partial x_i^2} - \mu \left\{ \frac{1}{3} \frac{\partial^2}{\partial x_i^2} \frac{\partial v_i}{\partial x_i} + \frac{\partial^2}{\partial x_i^2} \frac{\partial v_i}{\partial x_i} \right\} \quad (7)$$

Using (3) on the first term of (7) and interchanging the 'dummy' suffices in the last term gives

$$\frac{-\partial^2 \rho}{\partial t^2} + \frac{\partial^2}{\partial x_i \partial x_i} (\rho v_i v_i) + \frac{\partial^2 p}{\partial x_i^2} - \frac{4\mu}{3} \left\{ \frac{\partial^2}{\partial x_i^2} \frac{\partial v_i}{\partial x_i} \right\} = 0 \quad (8)$$

Equation (8) is still exact and may in fact be used to formulate a theory of sound generation following the methods of Lighthill (Reference 11). However, in order to proceed further it will be necessary to approximate, and from here on the fluid will be assumed to be incompressible.

With this approximation equation (3) becomes

$$\frac{\partial v_i}{\partial x_i} = 0 \quad (9)$$

and on using this result in (8) the last term vanishes. We see, therefore, that the viscosity has no direct effect on the pressure, and that even in a compressible

flow the effect of viscosity will only enter via the effect of compressibility. Thus, the last term in equation (8) may be ignored in all practical cases. This conclusion for local pressure fluctuations parallels that of Lighthill for sound radiation. Lighthill (Reference 11) showed that the inertia terms gave the leading contribution to the sound radiation, and in the present case the inertia terms are again the most important. For an incompressible flow the first term in equation (8) is also zero, although this term will certainly require consideration in any treatment of a compressible flow. However this first term will be ignored henceforth. Thus, for incompressible flows equation (8) becomes:

$$\frac{\partial^2}{\partial x_i \partial x_i} (\rho_0 v_i v_i) + \frac{\partial^2 p}{\partial x_i^2} = 0 \quad (10)$$

and this is the equation from which the pressure fluctuations may be calculated.

Now

$$\frac{\partial^2 (\rho_0 v_i v_i)}{\partial x_i \partial x_i} = \rho_0 \frac{\partial}{\partial x_i} \left\{ v_i \frac{\partial v_i}{\partial x_i} + v_i \frac{\partial v_i}{\partial x_i} \right\} \quad (11)$$

Using (9) the first term in (11) may be seen to be zero, leaving

$$\frac{\partial^2 (\rho_0 v_i v_i)}{\partial x_i \partial x_i} = \rho_0 \left(\frac{\partial v_i}{\partial x_i} \frac{\partial v_i}{\partial x_i} + v_i \frac{\partial}{\partial x_i} \left(\frac{\partial v_i}{\partial x_i} \right) \right) \quad (12)$$

And using (9) again the second term in equation (12) is zero so that equations (10) and (12) show

$$\nabla^2 p = - \rho_0 \frac{\partial v_i}{\partial x_i} \frac{\partial v_i}{\partial x_i} \quad (13)$$

If the velocities are now put equal to the sum of their mean and fluctuating parts

$$\left. \begin{aligned} v_i &= U_i + u_i \\ v_j &= U_j + u_j \\ p &= P + p' \end{aligned} \right\} \quad (14)$$

then the relationships for the mean and fluctuating parts of the variables may be established.

Putting relations (14) in equation (9) and taking means gives

$$\frac{\partial U_i}{\partial x_i} = 0 \quad (15)$$

since the mean of the fluctuating quantities is zero. Subtracting (15) from (9) shows also

$$\frac{\partial u_i}{\partial x_i} = 0 \quad (16)$$

Now putting relations (14) in equation (13) yields

$$\nabla^2 P + \nabla^2 p' = -\rho_o \left\{ \frac{\partial U_i}{\partial x_i} \frac{\partial U_i}{\partial x_i} + \frac{\partial U_i}{\partial x_i} \frac{\partial u_i}{\partial x_i} + \frac{\partial u_i}{\partial x_i} \frac{\partial U_i}{\partial x_i} + \frac{\partial u_i}{\partial x_i} \frac{\partial u_i}{\partial x_i} \right\} \quad (17)$$

and taking means

$$\nabla^2 P = -\rho_o \left\{ \frac{\partial U_i}{\partial x_i} \frac{\partial U_i}{\partial x_i} + \overline{\frac{\partial u_i}{\partial x_i} \frac{\partial u_i}{\partial x_i}} \right\} \quad (18)$$

Subtracting equation (18) from equation (17), and noting the identity of the middle two terms of the right hand side of equation (17) which differ only in their 'dummy' subscripts, gives

$$\nabla^2 p' = -\rho_o \left\{ 2 \frac{\partial U_i}{\partial x_i} \frac{\partial u_i}{\partial x_i} + \left(\frac{\partial u_i}{\partial x_i} \frac{\partial u_i}{\partial x_i} - \overline{\frac{\partial u_i}{\partial x_i} \frac{\partial u_i}{\partial x_i}} \right) \right\} \quad (19)$$

Note also that, by virtue of equation (16),

$$\frac{\partial^2 u_i u_i}{\partial x_i \partial x_i} = \frac{\partial u_i}{\partial x_i} \frac{\partial u_i}{\partial x_i} \quad (20)$$

So that an alternative form of equation (18) is

$$\nabla^2 p' = -\rho_o \left\{ 2 \frac{\partial U_i}{\partial x_i} \frac{\partial u_i}{\partial x_i} + \left(\frac{\partial^2 u_i u_i}{\partial x_i \partial x_i} - \frac{\partial^2 \overline{u_i u_i}}{\partial x_i \partial x_i} \right) \right\} \quad (21)$$

The right hand side of equations (19) and (21) have been split into two parts. The first term depends on both the mean shear $\partial U_i / \partial x_i$ and the turbulence intensity u_i whereas the second part of the expression depends only on turbulence intensities. These two parts correspond to the 'turbulence-mean shear' and 'turbulence-turbulence' contributions respectively.

2.2 Application to the Turbulent Boundary Layer

Suppose now, that equation (21) is applied to the case of the two-dimensional turbulent boundary layer. Ignore, for the time being, the nine component contribution of the turbulence-turbulence term. The contribution of the turbulence mean shear term may be written, in ordinary cartesian coordinates, as

$$\nabla^2 p' = -2 \rho_o \left\{ \frac{\partial U}{\partial x} \frac{\partial u}{\partial x} + \frac{\partial V}{\partial y} \frac{\partial v}{\partial y} + \frac{\partial U}{\partial y} \frac{\partial v}{\partial x} + \frac{\partial V}{\partial x} \frac{\partial u}{\partial y} \right\} \quad (22)$$

where U, V are the components of mean velocity along and perpendicular to the free stream direction and u, v are the respective fluctuating components.

The orders of magnitude of these terms can be calculated following the classic boundary layer approximation technique.

Equation (15) shows

$$O\left(\frac{U}{x}\right) + O\left(\frac{V}{\delta}\right) = 0$$

so that

$$V = O\left(\frac{\delta U}{x}\right) \quad (23)$$

where δ is the thickness of the boundary layer.

Using (23) in (22) gives the terms as

$$\nabla^2 p' = -2 \rho_o O(f) \left\{ O\left(\frac{U}{x}\right) + O\left(\frac{U}{x}\right) + O\left(\frac{U}{\delta}\right) + O\left(\frac{\delta U}{x^2}\right) \right\} \quad (24)$$

where the orders of magnitude of each of the fluctuating terms $O(f)$ has been taken as equal. Note that this supposition cannot be confirmed or denied for the case of a separated boundary layer since no experimental evidence is at present available. However this would seem to be a reasonable a priori assumption. In the attached boundary layer the data of Klebanoff (Reference 12), reproduced in Figure 2, indicate that the u fluctuation is about 50 percent larger than the v fluctuation. The magnitude of the lateral fluctuations falls between that of the u and v fluctuations.

When the boundary layer thickness (δ) is small it is clear from equation (24) that the major term of interest is the third. Equation (22) may thus be written

$$\nabla^2 p' = -2 \rho_o \frac{\partial U}{\partial y} \frac{\partial v}{\partial x} \quad (25)$$

and this equation has been the foundation of a number of attempts to predict boundary layer pressure fluctuations for the attached case (References 5 - 9).

However for the separated case these arguments are not valid. A discussion of the separated boundary layer will be put forward below, but first of all the formal solution to these equations will be written down.

2.3 Formal Solution of the Equations

The equations for the pressure fluctuations, from the original of equation (10) through its successive forms of (13), (19), (21), (22), and (25) are all of the Poisson type. The solution to this equation is well known. If a typical equation is written as:

$$\nabla^2 p = A(\underline{x}, t) \quad (26)$$

Then the solution in the absence of any boundary is

$$p(\underline{x}, t) = \frac{1}{4\pi} \int_V \frac{A(\underline{y}, t)}{|\underline{x} - \underline{y}|} d\sigma(\underline{y}) \quad (27)$$

Here \underline{x} is a vector describing the field point and \underline{y} is the 'dummy variable' of integration. There is an analogy between equation (27) and a solution to the wave equation which would be an identical integral, but evaluated at retarded time. This similarity has recently been used by Paterson (Reference 14) in an attempt to produce a simpler mathematical and physical model for the sound generation by turbulence. However, in the present case, we are necessarily interested in the evaluation of the integral at a wall. Here we follow Kraichnan (Reference 5) and include the effects of the wall through a mirror flow model of the turbulence field, so that the solution to (26) in the presence of a wall becomes

$$p(\underline{x}, t) = \frac{1}{4\pi} \int_{y_2 > 0} \{A(\underline{y}, t)\} \left(\frac{1}{|\underline{x} - \underline{y}|} + \frac{1}{|\underline{x} - \underline{y}^*|} \right) d\sigma(\underline{y}) \quad (28)$$

where \underline{y}^* gives the value of \underline{y} reflected in the wall, i.e.

$$y_1^* = y_1$$

$$y_2^* = -y_2$$

$$y_3^* = y_3$$

so that when the field point \underline{x} is actually on the wall $|\underline{x} - \underline{y}| = |\underline{x} - \underline{y}^*|$ and (28) becomes

$$p(\underline{x}, t) = \frac{1}{2\pi} \int_{y_2 > 0} \frac{A(\underline{y}, t)}{|\underline{x} - \underline{y}|} d\sigma(\underline{y}) \quad (29)$$

The presence of the wall has caused pressure doubling. Before considering equation (29) in more detail it is useful to return to equation (25) and apply simple similarity arguments to give the leading parameters governing the pressure fluctuations.

3.0 THE ATTACHED TURBULENT BOUNDARY LAYER

3.1 Similarity Arguments

It has been found that the turbulent boundary layer has a velocity profile which may be described - at least near the wall c. f. Figure 1 - by a one parameter family of profiles, the well known logarithmic velocity distribution due to Von Karman. This 'law of the wall' is

$$\frac{U}{U_{\tau}} = \frac{1}{k} \log \left(\frac{y U_{\tau}}{\nu} \right) + A \quad (30)$$

where k and A are experimentally determined constants. U_{τ} is the 'shear velocity' defined by

$$U_{\tau}^2 = \tau_o / \rho_o \quad (31)$$

Now equation (25) showed the pressure fluctuations to be dependent on the mean shear through the flow, and this may be found from the velocity profile of equation (30) as

$$\frac{\partial U}{\partial y} = \frac{U_{\tau}}{ky} \quad (32)$$

In addition the intensity of the fluctuating velocities through the boundary layer is proportional to the momentum transfer through the boundary layer, and thus

$$v = \alpha U_{\tau} \quad (33)$$

where α is a constant of order unity.

Using equations (32) and (33) in equation (25) shows that

$$\nabla^2 p' \sim - \rho_o U_{\tau}^2 \quad (34)$$

The constant of proportionality in this equation will depend on the typical eddy size and shape, i.e. on the correlation patterns within the flow.

Equation (34) establishes an approximate proportionality between pressure fluctuation and wall shear stress. It has been found experimentally that this proportionality gives a satisfactory description of the variations of pressure fluctuation in different attached turbulent boundary layers. Lilley has performed detailed calculations in Reference 6 and finds

$$p_{rms} = 3.1 \tau_o \quad (35)$$

The constant in this equation is found experimentally to be a slowly varying function of Reynolds number. The results from a number of experiments are reported by Bull (Reference 13) and generally lie within the range

$$2 < p_{rms} / \tau_o < 4$$

This simple relationship between pressure fluctuation and local shear is the result of the one parameter family of profiles that can be applied to the equilibrium attached turbulent boundary layer. It must be emphasized that any departure from such conditions will negate the conclusions reached above. For instance local wall roughness or free stream turbulence will affect the results. In particular there can be no reason to apply these results to the very different velocity distributions occurring in a separated flow.

3.2 Details of the Pressure Patterns

The arguments advanced above, although successful, have not given any detailed information on the pressure fluctuations. In order to obtain this information formal solution to equation (25) will be written down using equation (29).

The pressure fluctuation at the wall is thus

$$p = \frac{-1}{2\pi} \int_{y>0} \frac{2\rho_o}{r} \frac{\partial U}{\partial y} \frac{\partial v}{\partial x} d\sigma \quad (36)$$

Equation (36) has been written in terms of cartesian co-ordinates x, y, z , and r is the distance from the field point at the wall. A complete discussion of equation (36) would require a consideration of the correlation patterns for the velocity fluctuations. However, this refinement will not be considered during the present report, and the discussion will be limited to a consideration of the local interactions between the mean shear and the turbulence.

In order to draw some conclusions from equation (36) the data of Klebanoff have been analyzed in detail. This data gives the most complete information on velocity fluctuations at present available, and is thus particularly suitable for the determination of the pressure producing mechanisms within the boundary layer. Klebanoff did not make any measurements of the pressure fluctuation field but this is of no particular disadvantage in the present case as a direct comparison of magnitudes is not required.

Figures 1, 2, 3a, and 3b are from Klebanoff's report (Reference 12) and show the mean boundary layer profile, the velocity fluctuations, and the "dissipation derivatives" respectively. These dissipation derivatives are of particular interest since they also represent many of the pressure producing terms of equation (19). The term of particular interest is that of $\partial v / \partial x$ as this is the term which interacts with the mean shear in equation (36). But it will be noted that this term is one of the smaller derivatives plotted, and it seems that the Turbulence-Turbulence interaction of

$\frac{\partial u}{\partial x} \frac{\partial u}{\partial x}$ and $\frac{\partial u}{\partial z} \frac{\partial w}{\partial x}$ could be important in some cases. The mean shear for this boundary layer has been calculated and is shown in Figure 4. This figure has been derived by graphical differentiation of Figure 1 and may not therefore be

accurate, although it should show the main effects of interest.

Multiplication of $\partial v / \partial x$ from Figures 3a and 3b with $\partial U / \partial y$ from Figure 4 gives a measure of the contribution of each part of the boundary layer to the overall pressure fluctuation, and the result is plotted in Figure 5. Clearly, a major source of the pressure fluctuation arises in the part of the boundary layer closest to the wall, since both the mean shear and the velocity fluctuation are increasing rapidly in this region. It should be remembered however, that correlation patterns could have a marked effect on this conclusion. In Figure 5 the pressure contribution is plotted against local mean velocity, as it is thought that this allows a more meaningful interpretation to be made. Contributions from the part of the boundary layer below $0.5 U_0$ cannot be determined since $\partial v / \partial x$ is not given there. Measurement of the v component of fluctuating velocity requires the use of a cross-wire probe in the hot wire anemometer and the physical dimensions of this device preclude measurements near the wall. However in this "laminar sublayer" region the velocity fluctuations (particularly $\partial v / \partial x$) may be expected to be small. It is therefore thought that the contribution to the pressure fluctuation from well within this region will also be small.

Figure 5 is particularly interesting since it shows a major contribution to the pressure fluctuation to come from parts of the flow moving with velocities of around $0.6 U_0$ or less. This contrasts with the generally quoted result that the pressure field in the boundary layer is dominated by components moving at $0.8 U_0$.

Figure 6, taken from Reference 13, by Bull, offers a solution to this dilemma. This figure shows the apparent velocity of convection between two transducers, and has been determined from the time delay required for optimum correlation between the signals received from each transducer. At large transducer spacings the apparent convection velocity of the overall signal is indeed about $0.8 U_0$ but Figure 6 shows how this velocity approaches $0.53 U_0$ at zero spacing. This second figure is in

much better agreement with the arguments advanced above.

This variation in apparent convection velocity with transducer spacing has been reported by a number of authors (References 15, 16, 17), is usually explained as being the result of the variation in the distance for which various components of the flow are coherent. It does seem reasonable to suppose that the high frequency small wave length components of the flow will lose their coherence in a much shorter distance than the low frequency large wave length components. In addition it is not unreasonable to suppose that the small wave length components originate from the slower moving fluid near the wall while the large wave length components are emitted from higher mean velocity regions further out from the wall. These two arguments in combination do provide an explanation for the variation in convection velocity with spacing. The relatively rapid loss of coherence of the high frequency terms will result in the correlation at large spacings being dominated by the faster moving lower frequency pressure patterns. Additional experimental evidence supporting these arguments is presented in References 13, 15, and 17. However, some authors have not drawn the inescapable conclusion: i.e. that local pressure fluctuations are dominated by pressure producing phenomena near to the wall, with a typical convection speed of near $0.6 U_0$ or less. This agrees nicely with the arguments from the analysis of the data of Klebanoff put forward earlier.

The additional experimental evidence referred to above comes mainly from correlation measurements in narrow frequency bands. For this the transducer signals are passed through narrow band filters before correlation. Reasonable consistence is achieved for high frequency components in the various experimental investigations, but there is rather less agreement on the exact effects of the low frequency parts. In this discussion the "high" and "low" frequencies may be regarded as being roughly those with $\omega \delta^*/U_0$ greater and less than unity respectively. Bull (Reference 13) concludes that the high frequency components lose coherence after convection for about four wavelengths while the low frequency components lose coherence in a way which is not a function of wavelength. Willmarth and Woolridge conclude the

loss of coherence extends over four to six wavelengths for both high and low frequencies. Both sets of results show how the high frequency components are convected at a slow speed, around $0.6 U_0$, and the investigations also agree that the convection velocity of the low frequency components is near $0.8 U_0$ at large transducer spacings. However the exact effect of the low frequency components at small spacings is not clear. Bull's results for this case seem to lack internal consistency, and Willmarth and Woolridge's results do not admit a simple interpretation. This problem is considered further below.

3.3 Possible Flow Mechanisms

Although the effects of eddy coherence must be of practical significance, the "loss of coherence" hypothesis discussed in the last section is not the only mechanism by which the pressure fluctuation phenomena may be interpreted. In this section an alternative hypothesis is presented which is seen to provide a good explanation for many of the phenomena observed. The arguments presented are by no means conclusive, but do enable a better physical understanding of the causes of wall pressure fluctuations to be reached.

Suppose that the local pressure fluctuations at any time were dominated by the effects of a single eddy structure. Then the variation of convection velocity shown in Figure 6 could be simply the result of the outward movement of this eddy as it moved downstream. This outward movement would, of course, result in its attaining a greater convection velocity as it moved downstream. Using this idea Figure 6 may be used directly to predict a typical eddy locus, and this is plotted in Figure 7.

This locus represents weighted statistical average of all the eddies which have passed the transducer position. The weighting is provided by the pressure generation effects of each eddy, which may be expected to vary with distance from the wall. Thus care should be taken in drawing conclusions from this figure. However Figure 7 does give rise to some interesting speculations about the generation of pressure fluctuations in the turbulent boundary layer. It will be recalled that the arguments of the last section showed how a major source of pressure fluctuation, particularly of the high

frequency part of the fluctuation, was located near the edge of the laminar sublayer where the convection velocities are near $0.6 U_0$ (c.f. Figure 1).

In 1956, Einstein and Li (Reference 18) showed how the laminar sublayer suffered from an intermittent disintegration. This conclusion was supported by the work of Grant (Reference 19) and the mechanism has recently been the subject of a thorough investigation by Runstadler, Kline and Reynolds (Reference 20). It is found that the laminar sublayer convolutes itself into eddy structures which erupt away from the wall. Runstadler, Kline and Reynolds describe this as "the ejection of momentum deficient fluid from the wall", and Grant sees the mechanism as a "stress relieving motion". This powerful mechanism is at work near to the wall; in just the region where the highest contributions to the pressure fluctuations may be expected. It is not unreasonable to suppose, therefore, that a major fraction of the pressure fluctuations at the wall are a direct result of this intermittent eruption of the laminar sublayer.

This hypothesis implies that the pressure producing eddy is expanding away from the wall as it passes downstream just as was concluded above from the convection velocity measurements (c.f. Figure 7). Runstadler, Kline and Reynolds (Reference 20) have made visual observations of the eddies resulting from the disintegration of the laminar sublayer and found that the generation is random in space and time. However they were able to define typical paths taken by an eddy after generation from a statistical average of the many individual paths observed. This eddy locus is plotted on Figure 7 and may be compared with that predicted from the convection velocity measurements. The agreement is amazingly good, and provides powerful evidence in support of the hypothesis. The loss in agreement at downstream stations may be readily understood as being the result of the loss of coherence of the wall eddies. This would result in the convection velocities derived from correlation measurements reflecting a larger proportion of the higher speed eddies further away from the wall. But for eddies near to the wall the two plots are almost identical, and one can again infer that the eddies near to the wall dominate the pressure pattern.

However Figure 7 cannot be regarded as providing conclusive proof of the present hypothesis. As has already been mentioned the locus derived from the fluctuating pressure convection velocity measurements represents some sort of weighted average. In addition the variation of convection velocity used in the derivation of Figure 7 (from Reference 13) is not identical to that found in other investigations, (e.g. References 16 and 17). There is also a difference in Reynolds number between the two cases of Figure 7. Bull's work was accomplished at $Re_\theta \sim 20,000$ whereas the work of Runstadler et al had $Re_\theta \sim 2,000$. The agreement between the two cases of Figure 7 may thus be entirely fortuitous. Nevertheless, physical intuition suggests that if such a powerful "ejection" or "eruption" is taking place near to the wall, then it must be a major factor in producing the pressure fluctuations observed.

The writer feels that this mechanism probably provides all of the high frequency part and much of the low frequency part of the pressure fluctuations, and thus implies local convection velocities of $0.6 U_o$ or less for these fluctuations. The remaining part of the low frequency fluctuation probably arises much further away from the wall. It is interesting to speculate (although this is pure supposition) that it may occur through an identical eruption of the turbulent layer out into the free stream, as part of the known intermittent processes in turbulent flow. The relationship between the eruption of the laminar sublayer and the intermittency observed in the outer parts of the turbulent boundary layer has been pointed out in References 19 and 20 and this second phenomenon could well be a source of low frequency pressure fluctuations with a convection speed near $0.8 U_o$.

A further possible source of low frequency fluctuations is the effect of eddy accelerations, particularly in the intermittent part of the boundary layer. These have been shown to be a source of noise generation, and this aspect is discussed in Reference 21, which is enclosed with this report. This problem has also been considered by Ffowcs Williams (Reference 22) for the noise generation case. It seems probable that eddy accelerations could become particularly important sources of pressure fluctuation in high subsonic and supersonic boundary layers.

4.0 PRESSURE FLUCTUATIONS IN A SEPARATED TURBULENT FLOW

Equation (25) has been the starting point for most of the attempts to predict boundary layer pressure fluctuations. However, it cannot be applied to the present problem of the separated turbulent boundary layer. Firstly, it is by no means obvious that the "Turbulence-Turbulence" contribution to the pressure (the second part of Equation 19) can be neglected. In a separated flow high values of turbulence intensity are to be expected, and these could contribute substantially to the wall pressure fluctuations. However, until definitive measurements have been made in the separated boundary layer it will be difficult to make any final statement on the importance of this contribution. Clearly the turbulence intensities and correlation areas must be expected to be considerably higher than in the attached boundary layer. It may be possible to regard the outer region of the flow as part of a jet. Little work has been done on the pressure fluctuations in a jet, but there has been much interest in the parallel problem of the noise radiation. For this case investigations have shown (Reference 23) that the turbulence-mean shear interaction is dominant. In the absence of other information it may be assumed, for the present, that the same dominance is reflected for the case of pressure fluctuations in separated flow.

This leaves the turbulence - mean shear interaction of equation (22) as the leading source of pressure fluctuations. However this does not necessarily imply that its approximate form given in equation (25) is also valid. Equation (25) has been derived using the order of magnitude arguments presented in equation (24). While these cause no dissent for the case of an attached turbulent boundary layer, for a separated boundary layer δ may not be small compared to x . If the separation is taken to occur at angle of 17° , as indicated in the previous quarterly progress report of this contract (Reference 24) then the ratio of δ to x will be of the order 0.3. The contribution of the first two terms of equation (22) could thus be equal in magnitude to that of the third term. This will clearly result in an increase in pressure fluctuation and could have a major modifying effect on the correlation and frequency patterns encountered.

The two regions which may be expected to contribute most of these effects are the parts of the flow with maximum positive and negative velocity as it is here that the $\partial U/\partial x$ terms will be highest, but little can be said of the exact effects as no information on the structure of the turbulent boundary layer is at present available. A further complication in the theoretical treatment of these flows is that it may not be valid to assume homogeneity in the turbulence field. It is hoped that the projected experiments at Wyle Laboratories (see Appendix B) will help to show the true relative importance of the various terms in equation (22) for the separated case.

It is possible to make some general statements about the effect of the third mean shear ($\partial U/\partial y$) term in equation 22 on the pressure fluctuations. Figure 8 shows a conjectural velocity distribution for the turbulent separated boundary layer. It will be observed that the mean shear becomes large at two separate points in the flow. The first is near the wall. Here it may be anticipated that the law of the wall will apply, and that the pressure fluctuations from this part of the flow will be proportional to the wall shear stress as in equation (34). This contribution must be expected to be substantially lower than in the attached boundary layer since the velocity to which this shear is reacting is the velocity of the reverse flow, which is only a fraction of that of the free stream. The mechanism producing the pressure fluctuations from this region may again be that put forward in Paragraph 3.3, i.e. due to the direct influence of the intermittent eruption of the laminar sublayer.

The second region of high shear is the central part near to the "dividing stream-line" of the separated flow. The contribution of this region may be large. A separated flow grows at an angle perhaps ten times that of an attached flow, and this factor of ten is a measure of the total momentum transfer that is taking place through the flow. In the attached boundary layer this transfer is a result only of the wall shear stress, but in the separated boundary layer it is the interaction of the forward and reverse flows which gives rise to most of the momentum transfer terms. Momentum transfer in this second high shear region may thus be expected to be an order of magnitude larger than that near the wall in the attached boundary

layer case, with proportionate results on the wall pressure fluctuation.

Lilley and Hodgson (Reference 7) have investigated a similar flow with two regions of high shear using a wall jet. They also found the major contribution to the pressure fluctuations to come from this outer region. A particular feature of this outer region in the present separated flow case is that it is moving at a small fraction of the free stream velocity. The pressure fluctuation patterns resulting from this region would therefore be expected to have a low convection speed. In addition, contributions may be expected from the region of high negative velocity through the first two terms of equation (22), and this will again result in the prediction of a low overall convection velocity.

This conclusion is in opposition to the experimental work of Kistler (Reference 25) for supersonic separated flows. Kistler's work shows a convection velocity of about 0.6 of the local stream velocity. (Note that in his report the lower free-stream velocity behind the separation shock was not accounted for in the analysis). At this stage it is difficult to state where this discrepancy arises. It could be due to the effect of eddies in the outer part of the boundary layer entering via the first two terms in equation (22). If this is the case it will become apparent in the current low speed separated flow experiments planned at Wyle. On the other hand it would be due to effects associated with the supersonic flow, for example the eddy acceleration effects discussed at the end of section 3.3. Kistler's result could, in fact, be entirely due to shock effects. It is clear that the resolution of this discrepancy must form a central part of any theory to explain the pressure fluctuations in supersonic separated flows.

5.0 CONCLUSIONS

The equations governing the generation of pressure fluctuations in a boundary layer have been derived and the various approximations made have been noted. The most important approximation is the assumption of incompressibility. The equations have been written in a form which allows identification of the contributions of the "turbulence - mean shear" and "turbulence - turbulence" to the pressure fluctuation.

Both of these terms can be significant but the more important effect is usually the turbulence - mean shear interaction. For the pressure fluctuations in a two dimensional boundary layer, the equation takes the form

$$\nabla^2 p' = -2 p_o \left(\frac{\partial U}{\partial x} \frac{\partial u}{\partial x} + \frac{\partial V}{\partial y} \frac{\partial v}{\partial y} + \frac{\partial U}{\partial y} \frac{\partial v}{\partial x} + \frac{\partial V}{\partial x} \frac{\partial u}{\partial x} \right) \quad (22)$$

For the attached boundary layer the most important term will be the third, and the data of Klebanoff (Reference 12) has been analyzed to show the approximate contributions of the various parts of the boundary layer. The analysis shows that the major source of the pressure fluctuations lies near the edge of the laminar sublayer where eddy convection velocities may be expected to be about $0.6 U_o$ or less. It is shown how a proper interpretation of the results of space-time pressure correlation measurements gives the same conclusion. The quoted result of convection velocities near $0.8 U_o$ refers to the convection speed of the coherent low frequency eddies which dominate the correlations at large spacings, but only represent a small part of local pressure fluctuation.

It is suggested that the major part of the local wall pressure fluctuations could arise from the intermittent eruption of the laminar sublayer observed in flow visualization experiments. This does seem physically likely and the typical eddy path implied by the pressure fluctuation measurements following this hypothesis is found to agree with a typical eddy path actually observed in experiment, although this agreement may be

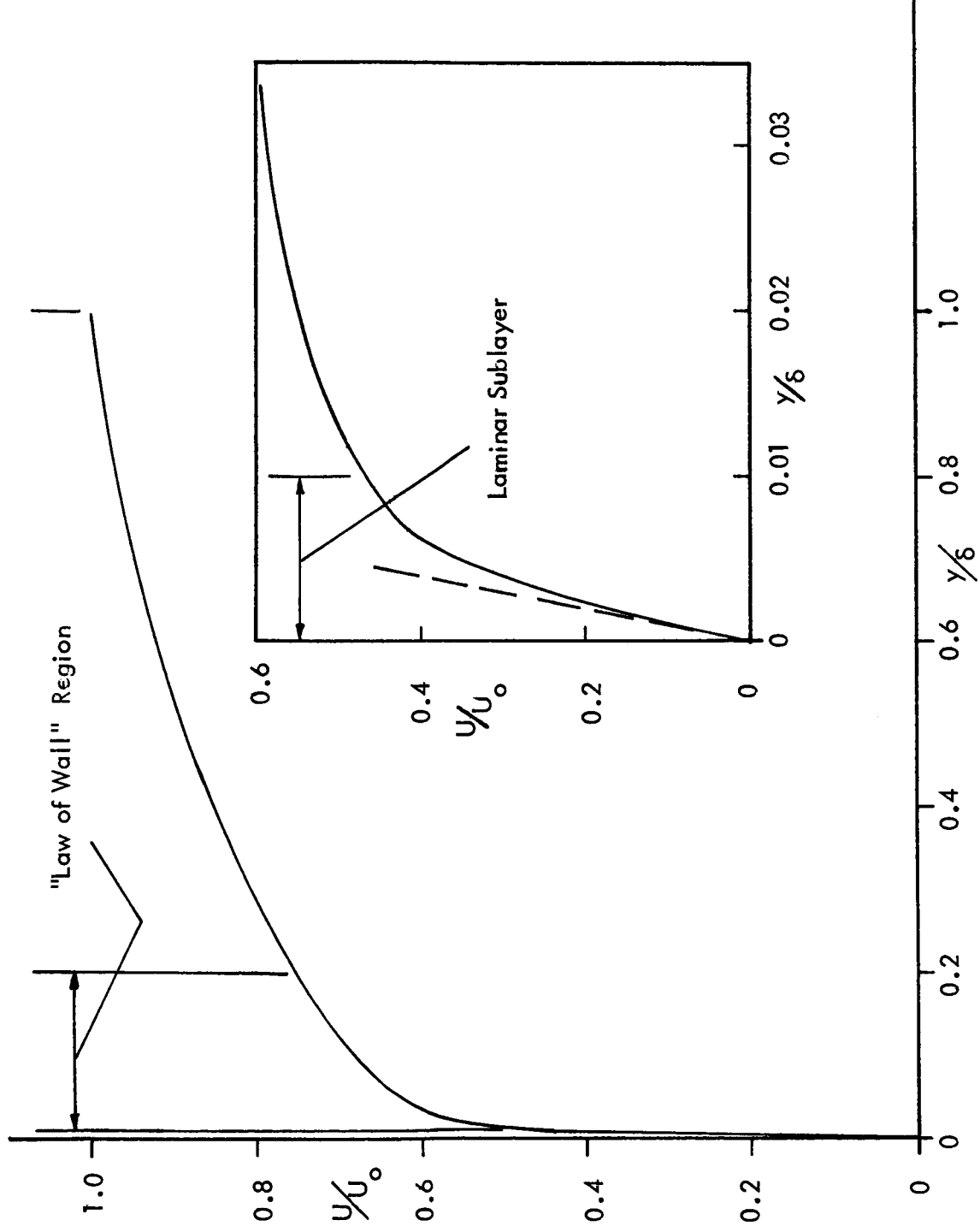
coincidental. A small proportion of the pressure fluctuation, confined to the low frequency region, is probably due to other parts of the boundary layer, the inner part of the intermittent region for example. A description of the pressure fluctuations as being mainly the result of laminar sublayer eruption agrees with all the known experimental facts, and provides a good model for a physical understanding of the forces at work.

The pressure fluctuations in a separated boundary layer have been discussed in the light of equation (22). It was shown how all the terms in this equation may produce a significant contribution to the pressure fluctuations observed. It was also shown that the third term in equation (22) could be expected to yield pressure patterns which were convected at near zero velocity. The other terms would not be expected to alter this conclusion, but it is radically different from the experimental result of a convection speed near to 0.6 of the local free stream velocity recorded by Kistler (Reference 25). This paradox was not resolved, but is thought to represent a fundamental problem in the analysis of the pressure fluctuations in separated flow. The possible modifying effects of the turbulence-turbulence interaction terms was noted but again no firm conclusions can be drawn until more experimental evidence is available.

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After Klebanoff
Reference 12

Figure 1: A Mean Velocity Profile for the Attached Turbulent Boundary Layer

From Klebanoff Reference 12

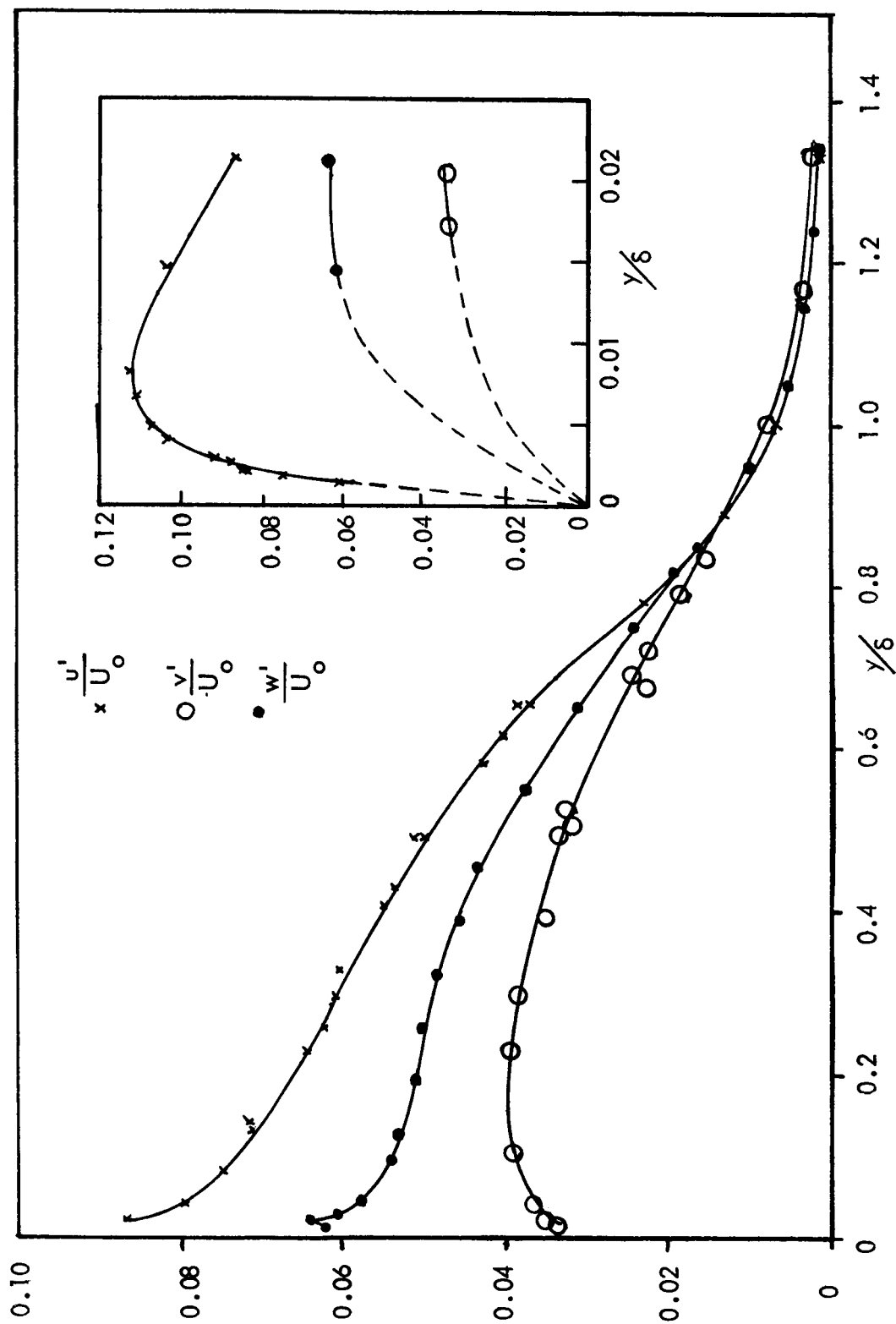


Figure 2: Distribution of Turbulence Intensities

From Klebanoff Reference 12

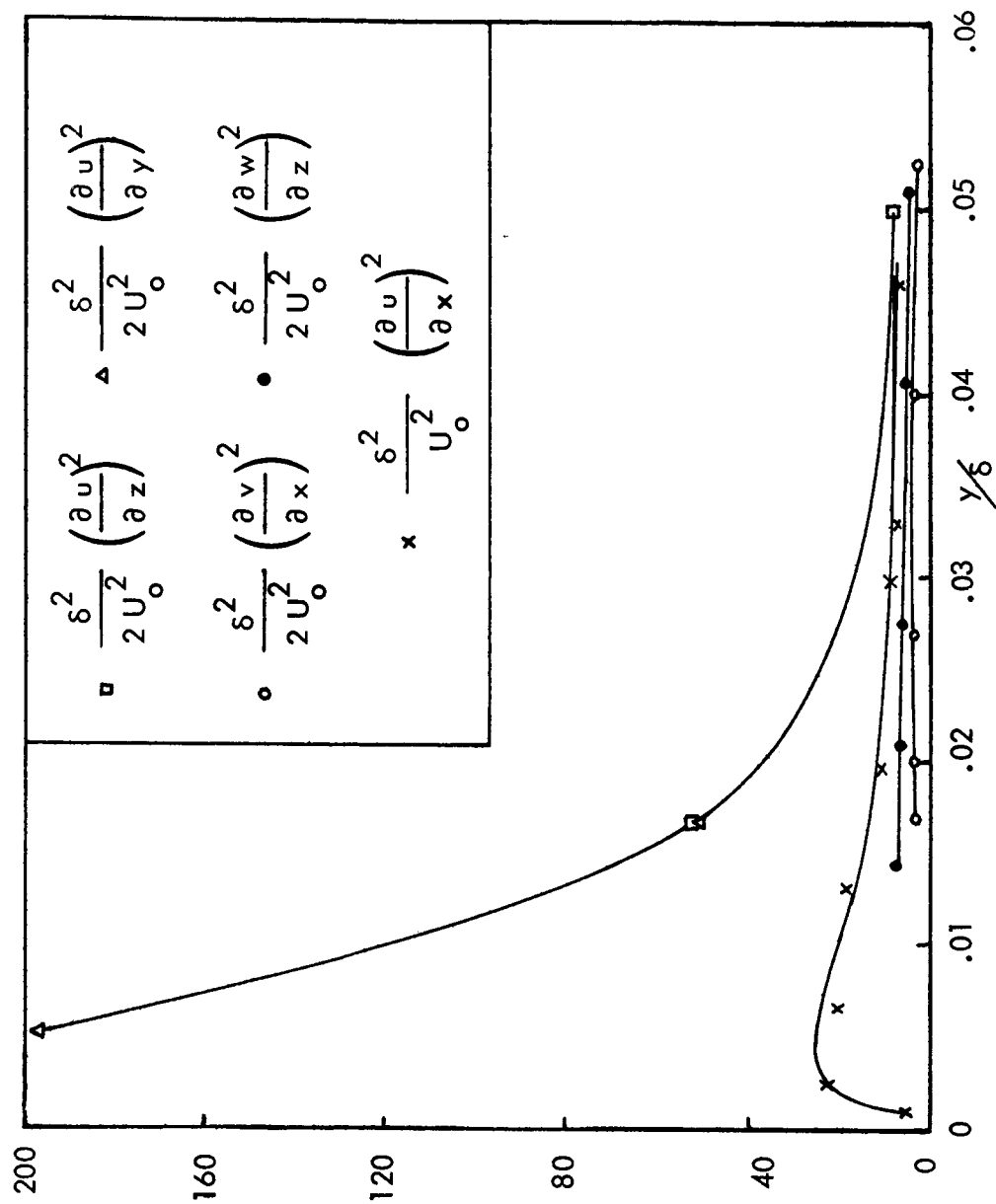


Figure 3a : Distribution of Dissipation Derivatives Near the Wall

From Klebanoff Reference 12

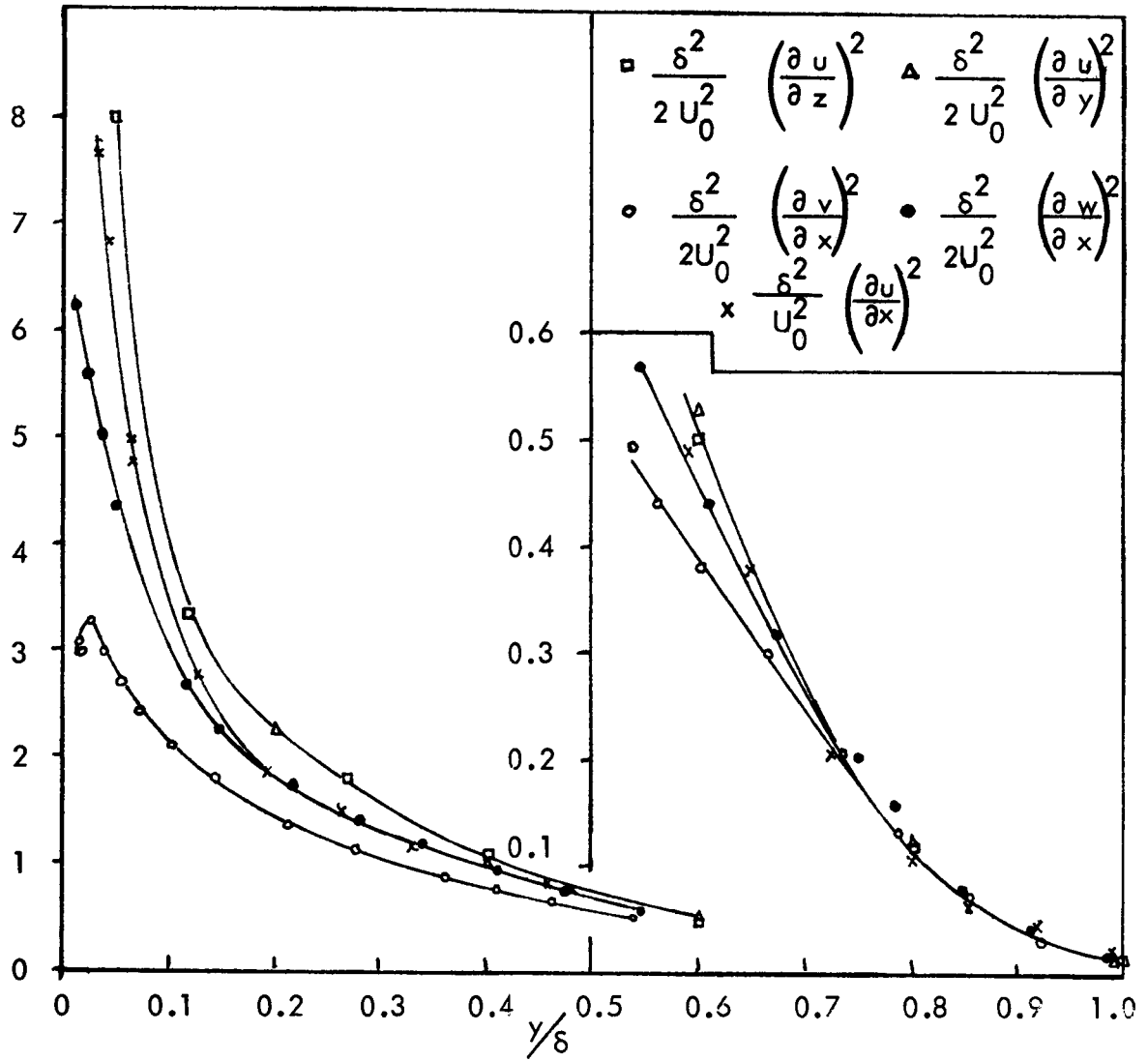


Figure 3b: Distribution of Dissipation Derivatives Away From Wall

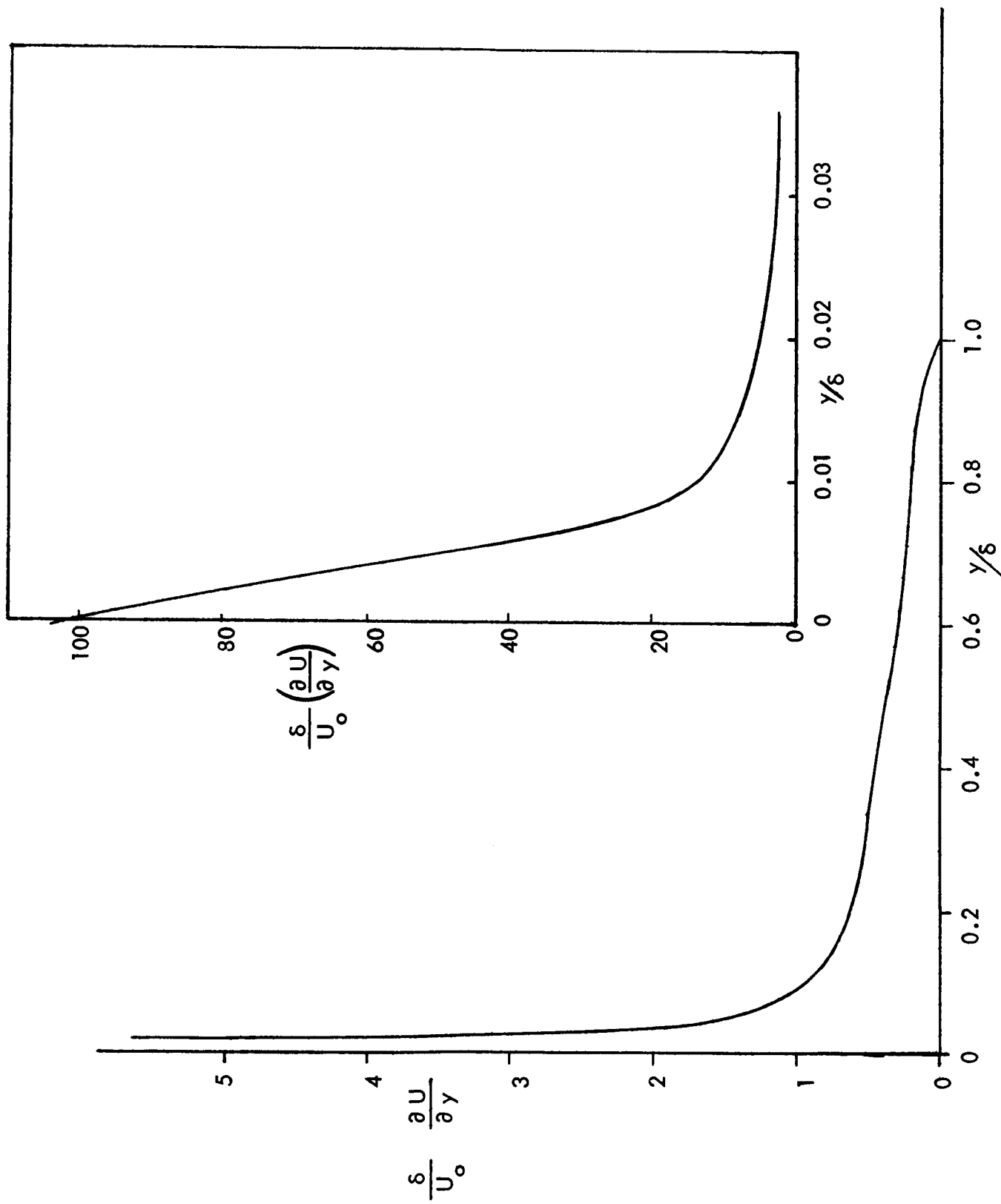


Figure 4: The Mean Shear Given By Figure 1

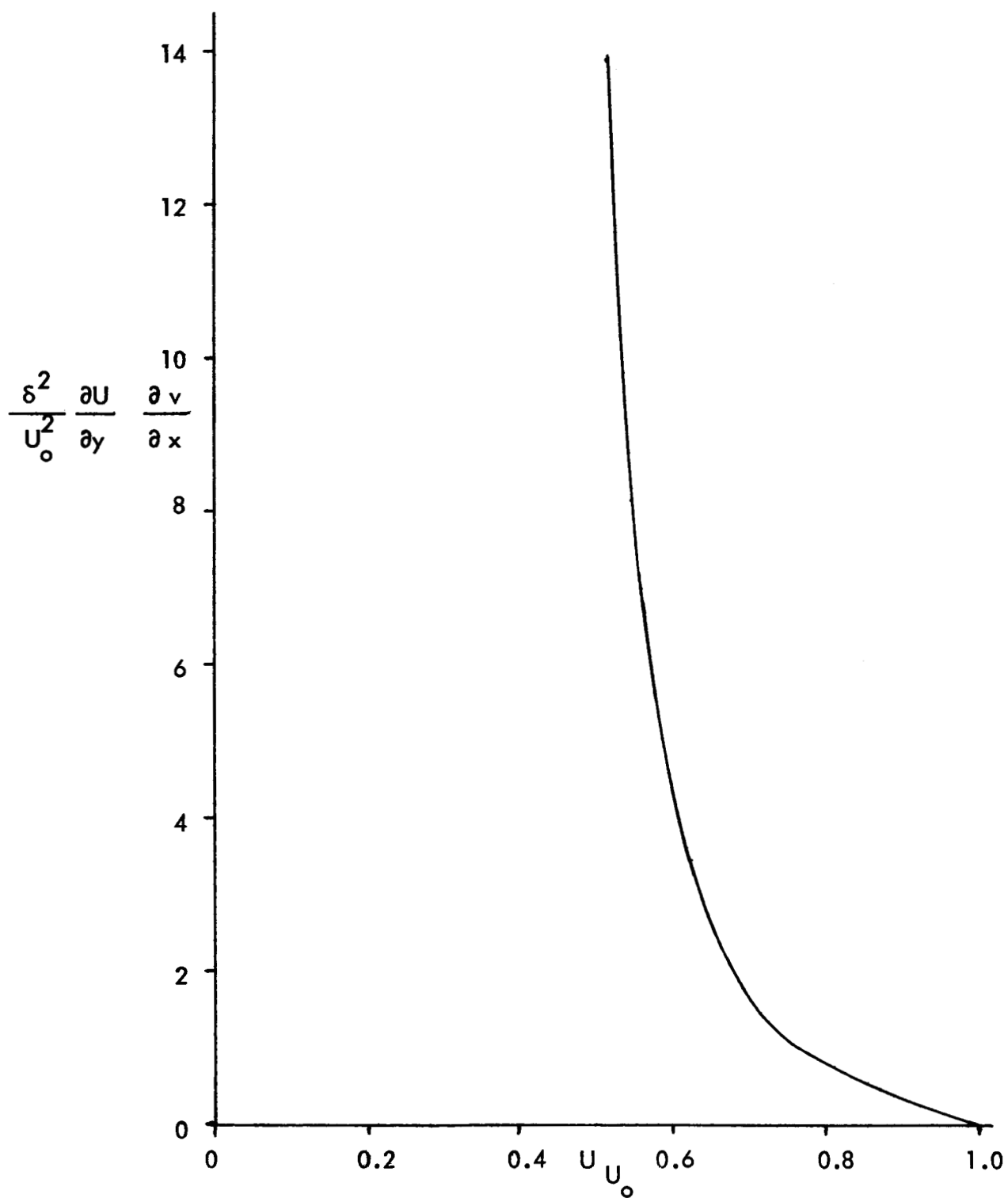


Figure 5: Contribution to the Pressure Fluctuation From Various Parts of the Boundary Layer

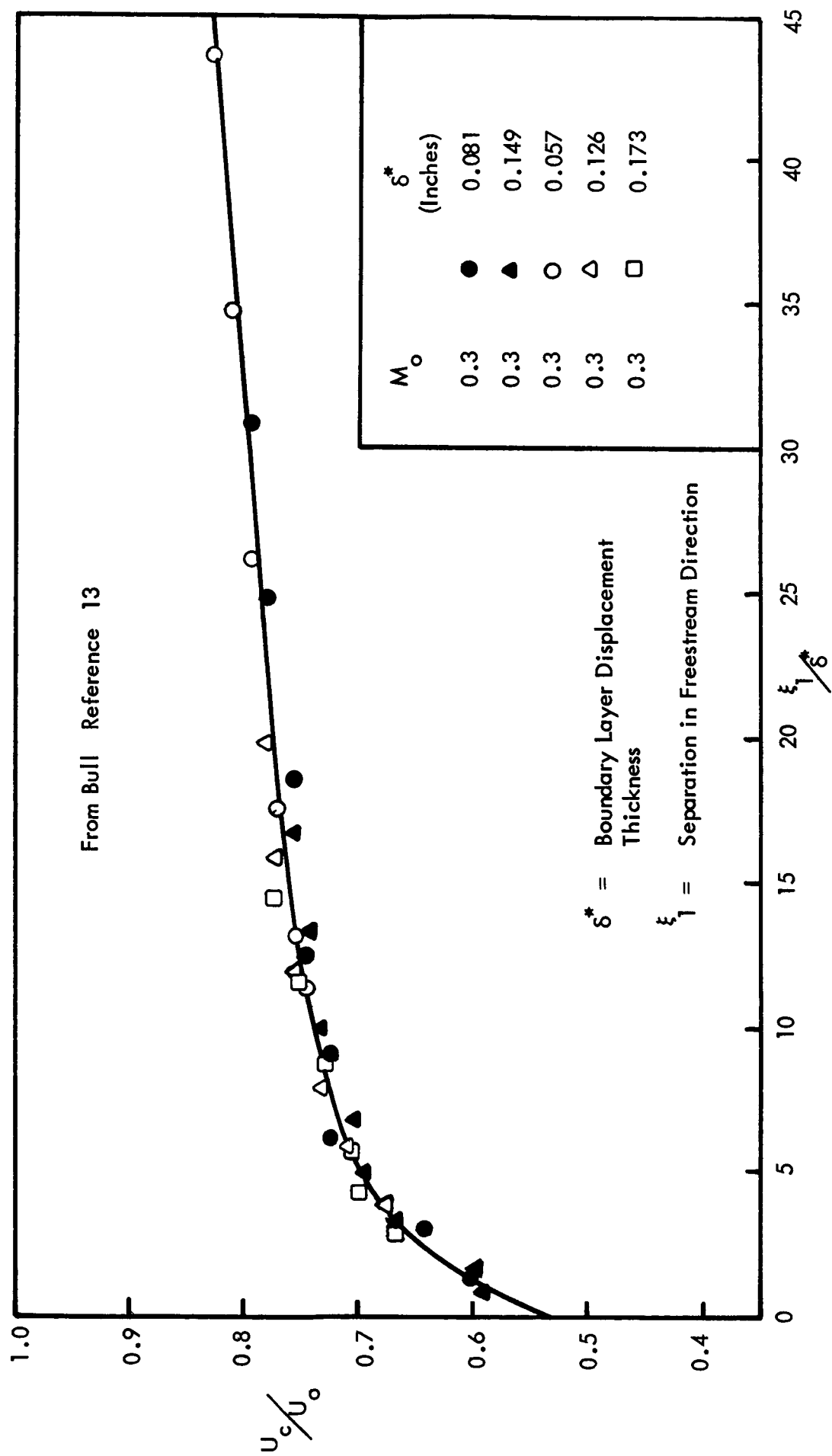


Figure 6: Variation of Convection Velocity With Spatial Separation

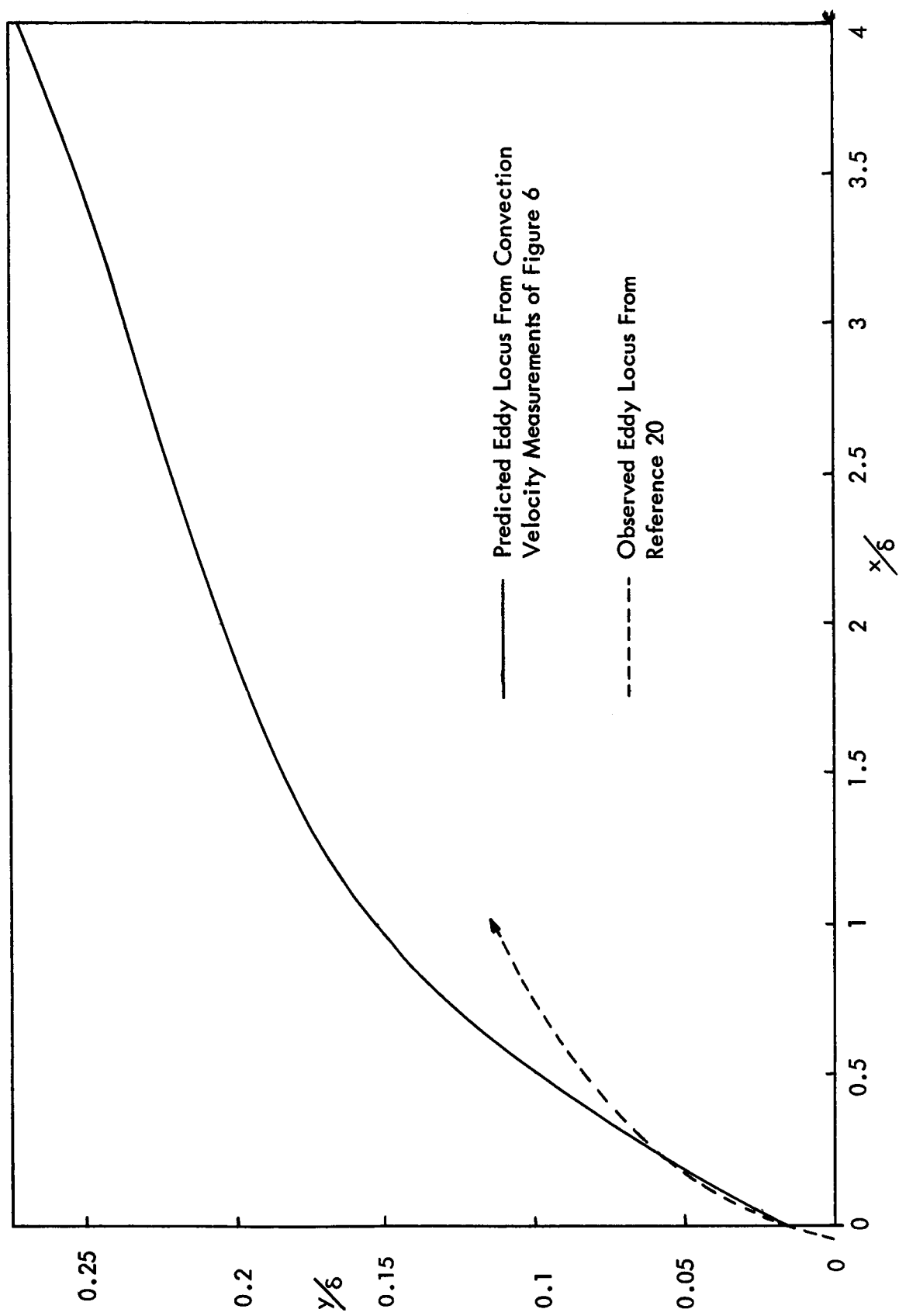


Figure 7: Predicted and Observed Eddy Loci After Eruption of the Laminar Sublayer

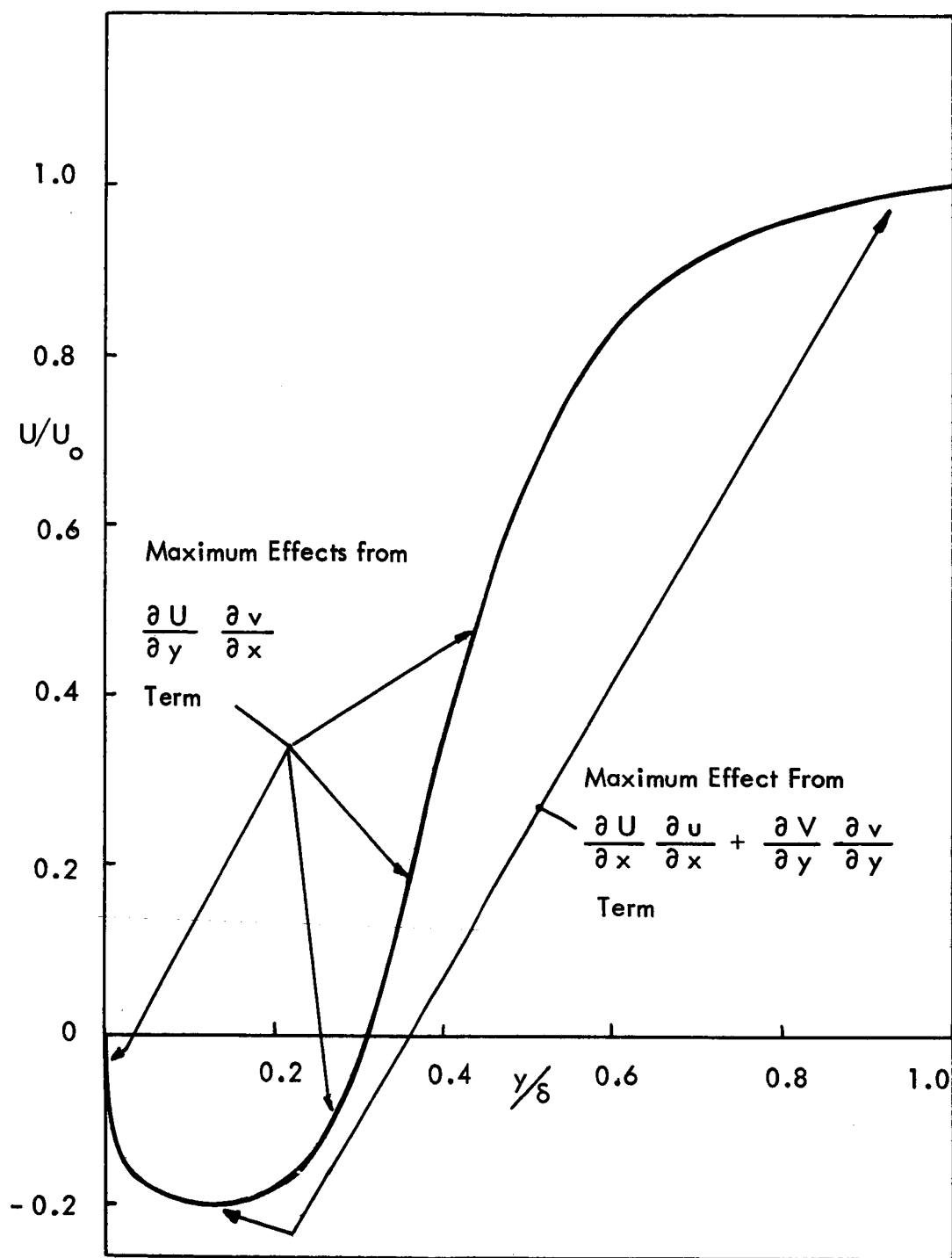


Figure 8: Conjectural Velocity Distribution for the Separated Turbulent Boundary Layer Showing Major Regions of Fluctuating Pressure Generation

APPENDIX B

THE EXPERIMENTAL PROGRAM

Introduction

Current attempts to produce prediction techniques for the pressure fluctuations in supersonic separated flow regions are particularly difficult because of the complete absence of any reliable information for the subsonic case. For the attached boundary layer the pressure fluctuations in the supersonic case may be predicted by a simple extrapolation from the subsonic case, (Reference 1), and the considerable amount of work performed in subsonic attached boundary layers is thus able to provide much useful information for the supersonic case. The present experiments are intended to provide a body of background information on low speed separated flows.

A particular advantage of the subsonic flow is that the separated region is shock free, so that the effects of pressure fluctuation due to turbulence may be considered in isolation from those due to shock patterns. The relative ease with which experimental data can be acquired in subsonic flows will enable a complete picture of the low speed flow to be built up and comparison with data from supersonic cases will then enable identification of the leading sources of pressure fluctuations present in the supersonic case.

The non-existence of experimental data on low-speed separated flows is very surprising. Pressure fluctuations in such flows are often of practical interest, (Reference 1), and in addition the problem is of considerable academic interest as a test for theoretical predictions of turbulence and pressure fluctuations. However the only published work on any type of separated flow seems to be that of Nikuradse (Reference 2) for the case of diffusers. The oft quoted work of Schubauer and Klebanoff (Reference 3) in fact deals with the flow parameters just before separation. Therefore, it does appear that the present work will fill an obvious gap in the literature.

Proposed Experiments

This complete lack of information on low speed separated flows makes it very difficult to decide which measurements should have priority in the program. However, one feature of the proposed experiments does seem necessary. In the supersonic case the mean wall pressure exhibits a rise over the forward part of the separated flow, followed by a "pressure plateau", or constant pressure segment, which usually constitutes the main part of the separated flow region. Reattachment of the flow causes a further departure from this plateau pressure over the aft part of the region. The reason for the existence of this plateau is clear when shadowgraphs of the flow are observed. The "separation shock" in front of the region is essentially straight so that the streamlines in the inviscid region behind the shock are also straight, and the free stream pressure behind the shock is forced to remain constant. In the subsonic case the streamline pattern is governed by the direct local interactions of the separation so that the free-stream pressures are not generally constant.

For the present experiments it is clearly desirable, as a first case, to study the development of separated regions without the complications of streamwise pressure gradients. This will eliminate one parameter from consideration, and also give a reasonable similarity to the boundary layer processes that occur in the supersonic case. It does introduce some complication into the design of the experimental apparatus, as will be discussed below, but the attraction of removing considerations of pressure gradient is overwhelming. This is, of course, the approach that has been adopted in the past for the attached boundary layer.

The problem of determining the proper priorities for measurement is still large. On the one hand it seems that direct measurements of the pressure fluctuations would be useful. Certainly it could be valuable to perform a complete analysis of the pressure fluctuations including spectra, correlation, and broad and narrow band convection velocities. But on the other hand it could be argued that hot wire measurements would give potentially far more useful information on the velocity fluctuations correlation patterns throughout

the flow. This information would show the most important regions of the flow following the theoretical methods outlined in Appendix A of this report. Clearly the proper experimental priorities can only be decided after careful consultation with M.S.F.C.

However it does seem apparent that the first objective must be the measurement of mean flow profiles at a series of points in the separated flow region. This information is fundamental to the analysis of either wall pressure or turbulent velocity fluctuations. Information on the mean flow profiles should also enable a theoretical attack to be mounted on the mean flow problem, and hopefully this would yield simple criteria for the estimation of rates of expansion, wall shear stress and other parameters of interest in the flow. It is hoped that these measurements will enable a simple family of profiles to be determined for the case of separated flow development in the absence of a free stream pressure gradient. Coles has shown in Reference 4 how many experimental velocity profiles for the turbulent boundary layer can be defined by a linear combination of a "wall" and "wake" velocity profile law. His analysis has successfully been applied to various cases near separation and it is hoped that the post-separation case will also fit his analysis. This would provide a very valuable understanding of the mean flow profiles in the separated region.

The experimental measurement of these mean flow profiles will not be as straightforward as is usually the case. For accurate flow velocity measurements the measuring tubes should be aligned with their axes parallel to the flow direction, but the unknown component of flow velocity normal to the wall adds much complication to the attainment of this condition. A further problem is that the stream-wise gradients of pressure and velocity present may prejudice measurements with pitot-static combinations. The static holes in such probes are set behind the pitot head and could be responding to different flow conditions. Fortunately both these problems can be overcome in a number of ways, either by attention during the taking of the experimental data or by correction after. Practical experience in these measurements will show the best method of approach.

Details of the Experimental Apparatus

The tests will be performed in a special working section incorporated into the Wyle low speed wind tunnel. A sketch of this wind tunnel is shown in Figure B 1. It has been specially designed for experiments in boundary layers, and features a unique muffler section to absorb noise radiated upstream from the fan. A second feature of the design is the "building block" construction. The five sections shown in Figure B 1 may be arranged in any order or replaced as desired. This enables a wide range of boundary layer thicknesses to be studied and allows for easy insertion of instrumentation blocks, etc.

The nominal cross-sectional area of the tunnel is 32" x 10" and the maximum speed of the tunnel is approximately 200 f.p.s. The arrangement shown in Figure B 1 allows an 8 foot run of boundary layer before the working section, which will result in a boundary layer thickness of approximately one inch. The acoustic environment in the working section is estimated as less than 80 db but will be confined to the blade passage frequency of the fan at 216 c.p.s. If this should prove troublesome for any particular experiment then it could be removed using a Helmholtz resonator. However, even an attached boundary layer will yield pressure fluctuations of around 110 db so that the internal noise of the wind tunnel at the working section is not expected to interfere with the experiments.

For the present series of tests the working section shown in Figure B 1 will be replaced by that shown in Figure B 2. As was discussed above the object of this section will be to provide a region of separated flow with zero free stream pressure gradient. It would be impossible to achieve this over the whole separated region but it is hoped that a major part of the flow will be free from any pressure gradient. Little is known of the geometry of separated flow patterns so that in order to achieve the desired flow with a constant pressure region a variable geometry section must be built. The final geometry that is actually used in the experiments will require experimental determination and will form the first and crucial part of the experimental program.

In this working section, as shown in Figure B 2, the flow separates at A, the constant pressure region is the central portion of BC and the flow reattaches at D. It will be observed that points B, C, and D may each be varied in position and this provides the variable geometry referred to above. The variation of point B is not essential for the generation of the flow but has been adopted so that a separated flow may be derived with minimum pressure rise down the working section. This pressure rise will occur on all four walls of the working section, and thus the geometry of the bottom wall could generate boundary layer separation at the top and side walls. In order to prevent this the bottom wall layer will be artificially thickened by sandpaper roughness in the upstream parallel section of the wind tunnel. This bottom wall boundary layer will thus be more prone to separation and it is hoped that, by minimizing the pressure gradient in the region AB, the bottom wall boundary layer will be persuaded to separate while the other wall boundary layers remain attached. If necessary additional boundary layer control devices will be introduced on the top and side walls in order to positively prevent separation. It is anticipated (Reference 5), that an expansion of area of between 10 percent and 20 percent will be sufficient to accomplish this, but expansions of up to 30 percent can be accommodated in the design. An additional advantage of this scheme is that the separated boundary layer may be expected to be nearer its asymptotic zero pressure gradient development profile after undergoing a small pressure rise. It should be noted however that this cannot be construed as a definite prediction as there is as yet no evidence as to the existence or non-existence of such a profile, or set of profiles.

The variation of point C is intended to provide the constant pressure region of the separation over BC. BC is, of course, a rigid wall and it is questionable whether a completely constant pressure region can in fact be established over BC. However the evidence from supersonic cases is that the combination of a shock induced constant pressure flow field and a straight wall does induce a substantially constant angle separation region. In the last Quarterly Progress Report (Reference 6), it was shown how this separation region does have a nearly constant angle which may be between 10° and 17° depending on flow parameters. Thus it is anticipated that the optimum

position of BC will be found to be at an angle of about 12° to the flow. The attainment of an exactly constant pressure region would certainly entail a more complicated wall geometry, but the provision of a completely variable geometry wall could not be justified in these experiments.

Reattachment will take place at point D which will require positioning in combination with the movement of point C. The lip at D is intended to provide a "clean" point of attachment for the flow, and it is hoped that this will remove the theoretical possibilities of instability which can be predicted for the reattachment point. The whole section is liberally instrumented with static pressure holes. Two lines of holes at one inch spacings run either side and four inches from the center line on both the top and bottom walls of the section. These are connected as required to a multitube manometer and will provide the first data by which the experimental geometry of the section is determined.

Initial Experimental Program

As was discussed above the proper priorities for the detailed measurements in the flow can only be decided after consultation with MSFC. However the initial program of work can be laid down

- 1) Generation of the constant pressure separated flow. Once this is achieved it will be necessary to perform a thorough "checkout" of the flow to ensure that the top and side wall boundary layers are attached, to check that the flow is two dimensional, etc. This check-out phase will probably consume some time.
- 2) Measurement of mean velocity profiles. The problems associated with this have already been discussed.
- 3) A "quick look" at the magnitudes of wall pressure fluctuation and turbulence intensity. This could be done at two stations in the flow and would give some initial information from which the future tests could be programmed.

Since so little information is available on this type of flow, it is very difficult to give a precise timing for these experiments. However it is hoped to have this initial part of the program complete before the next Quarterly Progress Report.

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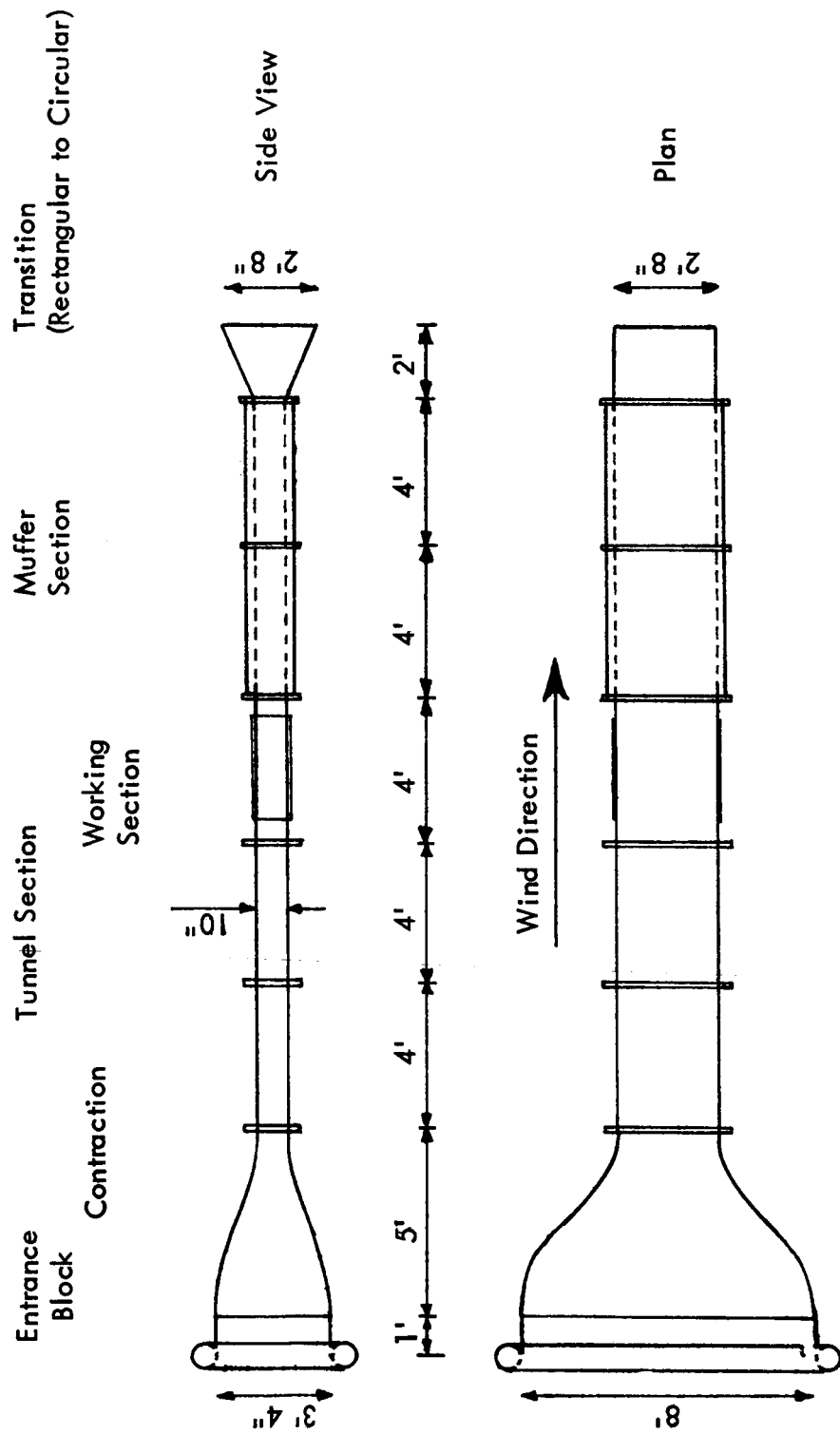


Figure B1: Sketch of Wyle Low Speed Wind Tunnel

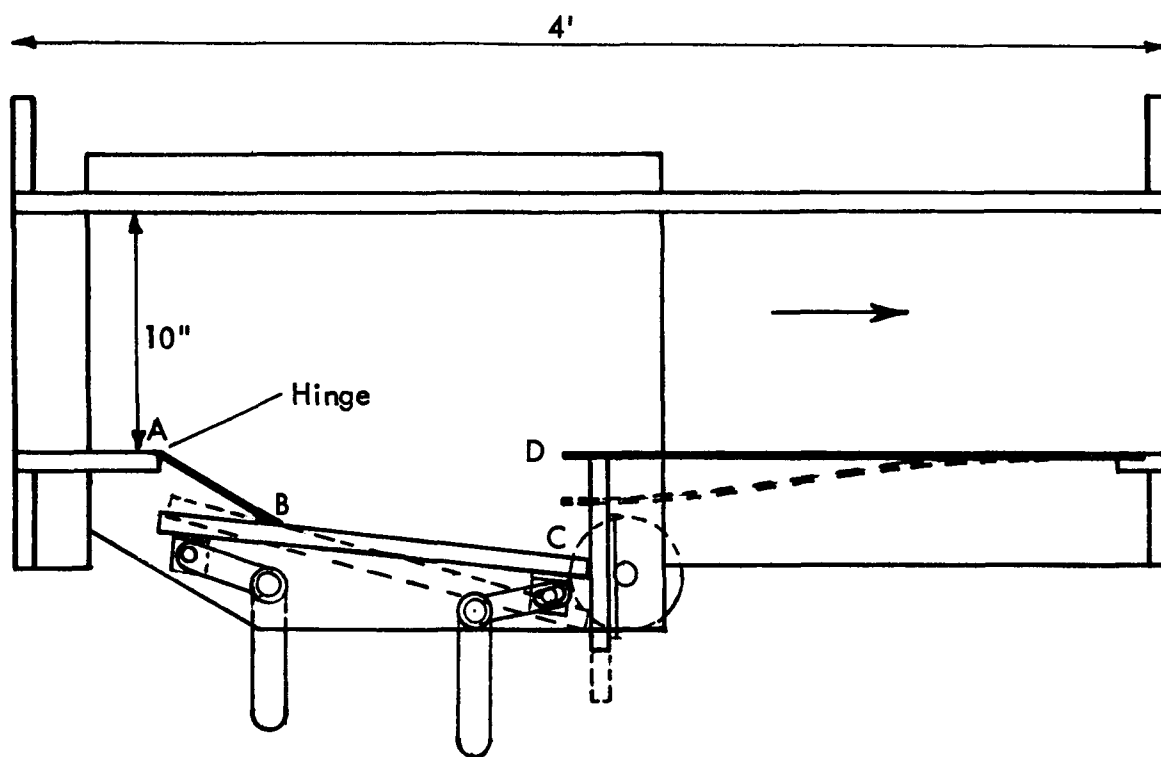


Figure B2: Sketch of Special Separated Flow Working Section